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Perspective

Hydrogen and ammonia fuelled internal combustion engines, a pathway to carbon-neutral fuels future

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ABSTRACT

Issues such as climate change and ever-increasing global warming have obliged governments and world authorities to comply with stringent regulations on the control of greenhouse gas (GHG) emissions in internal combustion engines (ICEs). Carbon dioxide (CO_2), the most produced GHG, has been the major concern of climate change in recent years. To reduce carbon emissions, fuels with lower carbon content, such as alcohol fuels, or fuels with no carbon content, like hydrogen and ammonia, should be taken into consideration to be replaced by fossil fuels in internal combustion engines.

1. Introduction

Hydrogen, as a fuel for combustion engines, has interesting features. The only combustion product of hydrogen is water vapor. Hydrogen has a great heating value per mass, about three times that of fossil fuels. Since hydrogen has a high adiabatic flame temperature together with lower radiation losses (because of the flame color spectrum), the efficiency of ICE will be higher. Hydrogen fuel has a high flame speed and high-octane number, i.e., high resistance to auto-ignition. These properties make hydrogen a good candidate for use in ICE and particularly spark ignition (SI) engines. Some advantages of utilizing hydrogen as a fuel are illustrated in Figure 1. Despite all mentioned favorable features, there are major issues with the feasibility of hydrogen-fuelled vehicles. Because of low density, huge storage containers are required. To store hydrogen in smaller tanks, there is a requirement to apply very high pressures or extremely low temperatures. High pressure (about 250 bar) for the case of gaseous hydrogen storage and low temperature (about 20 K) for storing hydrogen in the liquid phase. In addition, small hydrogen molecules tend to slip through the molecular structure of the container, so special materials are needed for making hydrogen containers. For utilization as the sole fuel in ICEs, hydrogen must be directly injected into the cylinder with very high pressures; otherwise, its extremely low density causes a massive reduction in engine volumetric efficiency. As a result, hydrogen is currently used mainly for combustion improvement alongside another main fuel, like natural gas or ammonia, in heavy-duty applications.

2. Ammonia Fuel

Ammonia is an inorganic chemical compound that is one of the most widely industrially produced chemicals. Ammonia is vastly used as a fertilizer in agriculture and also in refrigeration, water purification, and manufacturing plastics, rubbers, explosives, and other products. With 17.6 wt % (weight percentage), ammonia could be considered a hydrogen energy carrier, with the most hydrogen percentage among the liquid fuels. Besides the vast usage of ammonia in fuel cells as a hydrogen carrier, complete direct combustion of ammonia results in water and nitrogen, so it is considered a carbon-free green fuel.

Figure 1. Advantages of using hydrogen as a fuel [1]

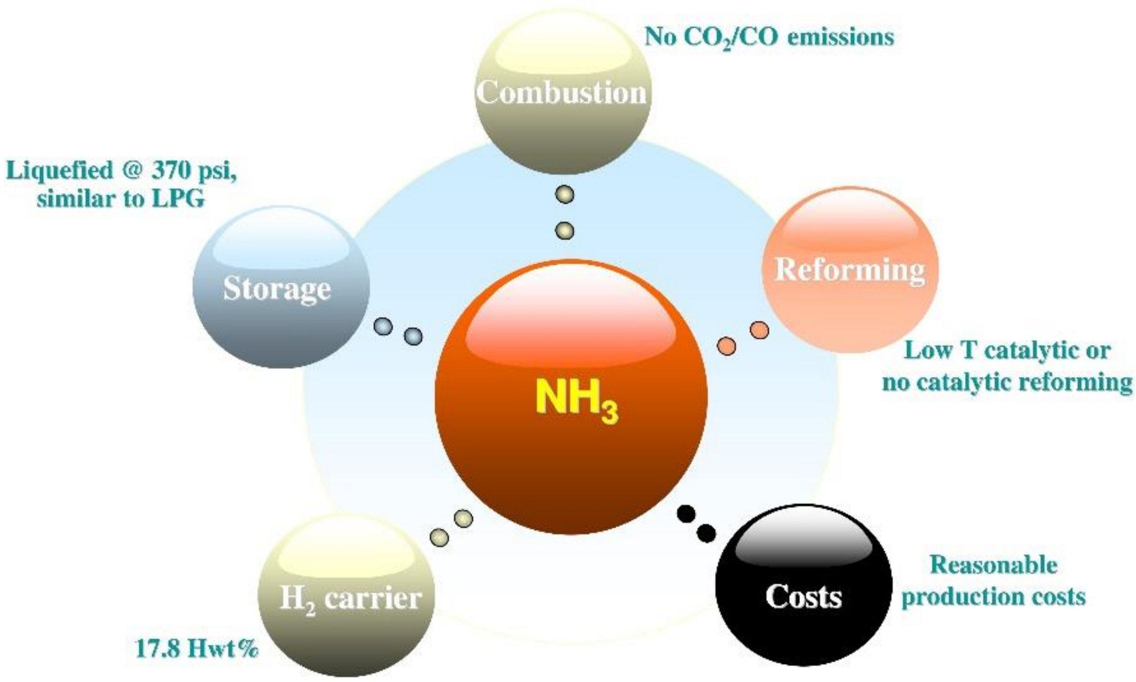

Figure 2. Advantages of using ammonia as a fuel [2]

Storage, transportation, and utilization of liquid ammonia are far more accessible and feasible than hydrogen, as it doesn't need high pressures or low temperatures, or special materials. Although ammonia has lower energy density compared to other conventional liquid fuels, e.g., gasoline and diesel, its high resistance to auto-ignition makes it suitable to use in engines with high compression ratios and also as an octane number enhancer additive. For the sake of comparison, some properties of ammonia, liquefied and gaseous hydrogen, and also conventional fossil fuels (natural gas, gasoline, and diesel) are presented in Table 1, and some advantages of using ammonia as a fuel are illustrated in Figure 2 [2].

3. Combustion Technology Considerations

To decrease the reliance on fossil fuels, there have been attempts to replace diesel fuel in engines with ammonia. Researchers have observed that ammonia is not a proper fuel to be utilized the same as diesel fuel, i.e., directly injected into the cylinder [3]. The reason is the high resistance of ammonia to auto-ignition, which necessitates very high compression ratios for compression ignition (CI) engines fuelled with ammonia. CI engines require fuels with good auto-ignition properties. With a high-octane number fuel, a CI engine has to operate at a very high compression ratio (around 35) to work only with ammonia. To make conventional diesel engines burn ammonia, a good approach is to utilize a dual fuel combustion strategy with a pilot injection of a highly reactive fuel (with a high cetane number) such as diesel, biodiesel, or dimethyl ether (DME). In this method, a high fraction of the total fuel, which could be even up to 95%, is ammonia, and similar to the conventional diesel engines, the pilot fuel is directly injected into the cylinder near the piston top dead center (TDC). The pilot fuel gets ignited due to the high compression temperature and causes the start of combustion in the primary fuel (in this case, ammonia), and then the flame propagates in the combustion chamber space.

Low-temperature combustion (LTC) methods are also investigated for ammonia fuelled engines. Ammonia has been used as fuel for different types of ICEs since the 19th century. For the first time, during World War II, in the shortage of diesel, ammonia was widely used in buses in Belgium as a fuel [5]. After the war, there was an approach for finding fuels to replace fossil fuels to decrease the dependency on oil. In recent years, the demand for the reduction of GHG emissions has been the motivation for industries and researchers to focus on partial or complete replacement of fossil fuels with ammonia. Because of the high resistance to auto-ignition, homogeneous charge compression ignition (HCCI) engines with only ammonia need rather high compression ratios and initial temperatures, which makes HCCI strategy impractical for this fuel. On the other hand, researchers have focused on the utilization of reactivity-controlled compression ignition (RCCI) strategy for ammonia.

In the RCCI engines, the low-reactivity fuel (e.g., ammonia) enters the cylinder as a mixture with the intake air. In the rather early stages of compression, a portion of a high-reactivity fuel is injected into the mixture. Then, near the piston TDC, the heat induced by compression starts the combustion in the mixture in regions that are rich in the high reactivity fuel, and then the flame propagates into the combustion chamber. One of the major issues concerning ammonia-fuelled engines, is high levels of emissions like unburned ammonia (NH_3), nitrous oxide (N_2O), and Nitrogen dioxide (NO_2). The main solution for the problem is pre-heating the engine intake air and also using selective catalytic reduction (SCR) after-treatment systems. Because of the need for spacious and heavy equipment, ammonia fuel seems to be more suitable for heavy-duty engines, like marine and power generation engines.

Table 1. Comparative properties of some fuels; ammonia, hydrogen, gasoline, and diesel [4]

Properties	Units	Ammonia	Hydrogen	Hydrogen	Natural gas	Gasoline	Diesel
Storage Method	–	Compressed liquid	Compressed liquid	Compressed gas	Compressed liquid	Liquid	Liquid
Storage Temp.	K	298	20	298	298	298	298
Storage Pressure	kPa	1030	102	24,821	24,821	101.3	101.3
Autoignition Temp.	K	924	844	844	723	573	503
Flammability limits (gas in air)	Vol. %	16 – 25	4 – 75	4 – 75	5 – 15	1.4 – 7.6	0.6 – 7.5
Absolute minimum ignition energy	mJ	8	–	0.02	–	0.14	–
Fuel density	(kg/m^3)	602.8	71.1	17.5	187.2	698.3	838.8
Lower Heating Value (LHV)	(MJ/kg)	18.8	120	120	45.5	44.5	43.4
Energy Density	(MJ/m^3)	11,333	8539	2101	8517	31,074	36,403
Octane Rating	(RON)	110	>130	>130	107	90 – 98	–

4. Conclusion

Due to global concerns about the emission of greenhouse gases, there has been an approach in both research and industrial sectors to utilize carbon-neutral fuels such as hydrogen and ammonia in IC engines. Hydrogen has very good chemical properties as a clean fuel, but its storage and transportation are difficult, costly, and with safety issues. Ammonia is a chemical compound that could be considered a hydrogen energy carrier with massive worldwide production and rather unchallenging storage and transportation. Ammonia has conveniently been used in SI engines, but for heavy-duty CI engines, it is required to employ such strategies as pilot-ignited dual fuel and also RCCI combustion modes.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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